Grain-size distributions of sandy sediments - sieving versus settling

PingYin, Søren Vinsløv & Jesper Bartholdy

Abstract

Settling analysis are becoming common practice in many sediment laboratories. By analysing sieved sand fractions of varied sample weight in a settling tube, it was found that the optimal sample size for the settling analysis can be calculated as (SI-units):

Sample size = $55.4\ d_{siv}\ (d_{tube})^2$. Grain-size distributions based on settling analysis, differ systematically from those of traditional sieve analysis. The differences between the two methods have been examined in sediments from four different sedimentary environments in the southwest of Denmark. Samples from rivers, the Wadden Sea, the North Sea coast and aeolian dunes gave a mean relationship between sieve diameter and settling diameter: $d_{set} = 0.8169 d_{siv} + 0.3555$. This relationship is almost identical to that observed in sediments from the East Frisian Wadden Sea. Thus, the settling diameters are larger than the sieve diameters for sand finer than approximately 2 phi (0.250 mm) and smaller for coarser grain sizes. This trend results from a larger volume diameter in the fine grain-size classes combined with the well known feature that the hydraulic resistance of irregular grains increases as the settling velocity becomes larger. Comparing sieve-based textural parameters with their settling-based counterparts, the following trends were observed: 1) sieve-based grain sizes finer than 2 phi correspond to coarser settling diameters, while coarser sieve-based sand fractions correspond to finer settling diameters; 2) the sorting gets better; 3) generally, fine well-sorted sediments with a negative skewness become more negatively skewed, whereas coarser and less well-sorted sediments become more positively skewed, and 4) the kurtosis of the distributions increases for well sorted sediments. The pattern is very clear for the mean grain size and the sorting, but less obvious, for the skewness and the kurtosis.

Keywords

Sand, grain-size analysis, grain-size distributions, settling velocity, settling diameter, sieve diameter.

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In the past, grain-size distributions of sandy sediments have been almost exclusively determined by sieve analyses. Using this method, sand grains are sorted into discrete size fractions according to their ability to pass through or to be retained on stacked sieves with progressively finer mesh sizes. The length of the square openings defines the size range of the individual fractions. As a result, the separation process is not only related to the physical size but also to the shape of a particle and the translation of sieve diameters into geometrically defined grain sizes is difficult (e.g. Syvitski, 1991). To simplify matters, the sieve grain size is often referred to as the volume diameter, i.e. the diameter of a sphere with the same volume as the particle. It is easy to imagine how a large elongated particle is able to pass through a sieve opening which will retain a spherical particle with a much smaller volume. This drawback, and the fact that in nature it is the combined characteristics of a grain i.e. grain size, shape, density and so on that control the grains ability to move and become "size" sorted, has inspired many sedimentologists to also consider the particle density and/or shape as supplementary parameters to the sieve diameter (e.g. Corey, 1949; Hallermeier, 1981; Komar & Reimars, 1978). Such considerations were also fundamental in early attempts to link settling velocity to grain size (e.g. Rubey, 1933; Rouse, 1936). Other approaches concentrated on the actual behaviour of sand in transport (e.g. Winkelmolen, 1971), but has not achieved wide acceptance. In contrast, the settling velocity is today generally considered as the best indicator of the hydraulic behaviour of sand grains in natural sedimentary environments (e.g.Reed et.al., 1975; Flemming & Thum, 1978). However, settling velocity depends on the water as well as on the grain properties. In order to restrict the analysis solely to grain size, and still to respect the settling velocity as the most important parameter, "the equivalent sphere diameter", which is defined as the diameter of a smooth sphere with the same density and the same settling velocity as the grain in question, was chosen as the grain size indicator.

Modern equipment which allows routine grain-size analyses of sand-sized particles by measuring their velocity distribution and converting these into equivalent settling diameters, is becomming more common and is favored by many sedimentologists. This is not only because the settling diameter is regarded as superior to the sieve diameter as an environmental index parameter, but also because such analyses are much easier to carry out while achieving a much higher resolution. Using the equipment developed by Brezina (1979), the normal sieve based 1/4-phi resolution can be improved by a factor of more than 10.

Since the vast majority of studies dealing with sediments make use of grain-size data derived either on sieve or settling analysis, it is natural to enquire how such data sets compare and if the combined information can provide us with additional knowledge. Comparing the statistical parameters using the log-hyperbolic distribution in a study of beach, lake and aeolian sediments, Lund-Hansen & Oehmig (1992) found that textural characteristics such as kurtosis, skewness and sorting varied strongly according to the choice of method (sieve diameter versus settling velocity). By systematically comparing the results of sieve and settling analyses of sand samples taken from sedimentary environments in the Danish Wadden Sea and adjacent coastal and fluvial environments, the objectives of this paper are: 1) to describe the differences observed in grain-size distributions obtained by the two methods *and* 2) to explain the difference and to construct the necessary definitions and algorithms for the mutual use of settling and sieve data.

Methods and definitions

The tidal flat, beach and aeolian samples were collected from the upper 2-3 cm of the sediment surface by filling a small cylinder with 3-5 randomly distributed sub-samples at each location. Where bedforms were present, sampling in the troughs was avoided. The river samples comprised the top 2-3 cm of sediment cores collected by means of a tube sampler. The samples (approx. 15-25 g dry weight) were wet sieved through a 4 phi (0.063 mm) sieve, after ultrasonic treatment in a solution of $Na_4P_2O_7$, using demineralized water in order to remove the mud fraction and possible remains of salt. The remaining sand fractions were dried to a constant weight. *When sieved*, the dry sample was placed on top of a 1/4-phi sieve column (ASTM-certificate) and shaken for 20 minutes. The contents of the single sieve were weighed with an accuracy of 0.001 g. *When analysed for the settling diameter*, the dried sample was sieved through a -1 phi (2 mm) sieve. The coarser fraction was weighed and stored for possible later sieve analysis. The sand fraction was split into approximately 1-2 g subsamples (the optimal size, see below) using a "Microscal SR1AB Spinning Riffler" sample splitter. In each case, 2-4 subsamples were analysed in the settling tube (Macrogranometer, see Brezina, 1979) and afterwards combined into one mean sample. The fraction coarser than 2 mm is not suitable for analysis in the Macrogranometer, primarily because of the very sensitive balance which "feels" the impact of larger grains and produce spurious spikes on the cumulative weight curve.

The grain size is described using the phi scale (Krumbein, 1934), where the diameter (d) is defined as the negative binary logarithm of the diameter measured in mm:

$$d_{phi} = -\log_2(d_{mm}) \qquad (1)$$

As the phi unit is dimensionless, the diameter should be divided by the unit value of 1 mm before extracting the $\log_2$ of the diameter (McManus, 1963).

The recorded settling velocities, determined from relationship between the length of settling tube and the time it takes for the particles to settle through the water column, are converted into equivalent spherical grain diameters and vice versa by balancing the gravitational and fractional forces:

$$w_s = \sqrt{\frac{4(s-1)gd}{3C_d}} \qquad (2)$$

$$\Longrightarrow$$

$$d = \frac{3w_s^2 C_d}{4(s-1)g} \quad \Lambda \quad C_d = \frac{4d(s-1)g}{3w_s^2} \qquad (3)$$

Where w_s (m s^{-1}) is the settling velocity, g (m s^{-2}) is the acceleration due to gravity, d (m) is the diameter of the settling sphere, (s-1) is the ratio between the submerged density of the grain and the density of water [$(\rho_s-\rho)/\rho$] and C_d is the dimensionless hydraulic drag coefficient.

Brezina (1979) describes a series of equations by which it is possible to calculate the drag coefficients of particles, with different shape factors, as a function of their Reynolds' number: $R_* = w_s d/\nu$; where ν (m^{2}s^{-1}) is the kinematic viscosity, which is related to the dynamic viscosity μ (kg m^{-1}s^{-1}) by $\nu = \mu/\rho$ with ρ (kg m^{-3}) as the water density. Brezina (1979) suggests the use of the Corey Shape Factor (Corey, 1949) which combines the long (d_L), the intermediate (d_I) and the short (d_s) grain diameter by the following relationship:

$$S_F = \frac{d_S}{\sqrt{d_L \cdot d_I}} \qquad (4)$$

Defining the shape of a particle by means of this relationship can only be regarded as an approximation and the relationship between fall velocity and the particle size is therefore hard to define exactly for the irregular shape of naturally worn particles, even if they are separated into shape groups according to Equation 4. In order to avoid unnecessary confusion, the equivalent settling diameter of a particle (d_{set}), is here defined as that of a smooth sphere, with the same settling velocity, following the choice of Flemming & Ziegler (1995). Thus, in terms of C_d and R_* any equivalent settling diameter can be calculated by iteration from the relationship:

$$C_d = 24.026R_*^{-1} + 4.059R_*^{-0.5} + 0.38873 \qquad (5)$$

when C_d is replaced with the expression for C_d in Equation 3 (Brezina, 1979).

The statistical parameters of the grain-size distributions were calculated on the basis of percentiles following Folk and Ward (1957), with a small adjustment changing 16th and 84th percentile into 15.866 and 84.134 respectively, in order to apply the precise expression derived from the relationship between the sorting parameter, and the standard deviation calculated as the second moment of the distribution.

Results

Sample size

When using the Macrogranometer, a key question is the choice of sample size. On the one hand it is desirable to analyse as large a sample as possible in order to secure statistically representative particle numbers, but on the other hand, if the introduced sample is too large, it will form a convective cloud resulting in artificially increased settling velocities affecting in particular the finer particles. Based on a size range of sieved 1/4-phi fractions, this problem was dealt with as illustrated in Figure 1. These results suggest that the introduction of a sample size with a dimensionless areal concentration (α) of less than 0.04

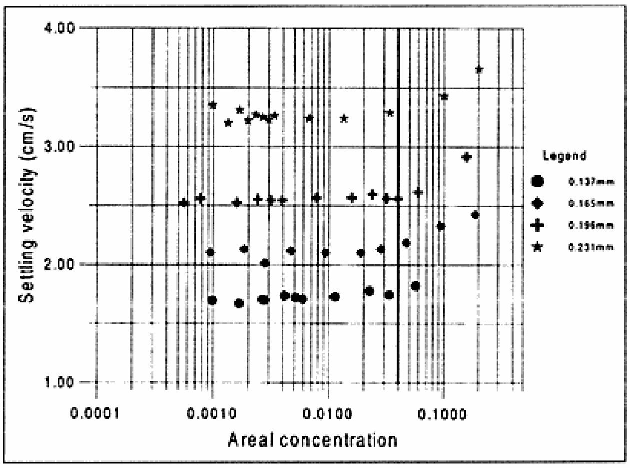

Figure 1: Settling velocity of four (1/4-phi) sieved fractions (0.150-0.125 mm, 0.180-0.150mm, 0.212-0.180 mm and 0.250-0.212 mm) as a function of the initial areal concentration (projected grain area/tube area) of grains at the introduction level of the Macrogranometer. The solid vertical line at the areal concentration of 0.04 indicates (by visual inspection) the estimated concentration beyond which the settling velocity is artificially increased.

will ensure that the results are not influenced by an artificially increased settling velocity.

Defining the areal concentration as $\alpha = n \cdot d_s^2 / d_{tube}^2$, with n being the number of particles defined by the sample weight divided by the grain weight (n=sample weight / $\pi/6 \cdot d_s^3 \cdot \rho_s$), and d_s and d_{tube} the diameter of the grain size and the settling tube respectively, this relationship can be used as the basis for a simple equation giving the maximum sample weight as a function of grain-size and tube diameter in SI-units:

$$\text{Maximum Sample weight (kg)} = 0.04 \cdot \rho_s \cdot \pi/6 \cdot d_s \cdot d_{tube}^2 = k \cdot d_s(m) \cdot d_{tube}(m)^2 \quad (6)$$

where k has a constant value of 55.4 (kg m^{-3}).

For the used Macrogranometer with a tube diameter of 0.305 m this equation becomes:

$$\text{Maximum Sample size (kg)} = k' \cdot d_s(m) \quad (6')$$

where $k' = 5.2$ (kg m^{-1}).

This last equation also holds for the sample size measured in grams and the particle diameter measured in millimetres. The maximum sample sizes determined in this way are "on the safe side" as they are based on the extremely uniform material in the sieved sample fractions. In natural sand, the different settling velocities will quickly disperse the particle cloud. Figure 2 displays the grain size distributions of four 1 g splits (following eq. 6) of the same sample, illustrating the high degree of reproducibility. Results by Vinsløv (1998) suggest that this also holds for medium sized particles with a sample size of about 2 g.

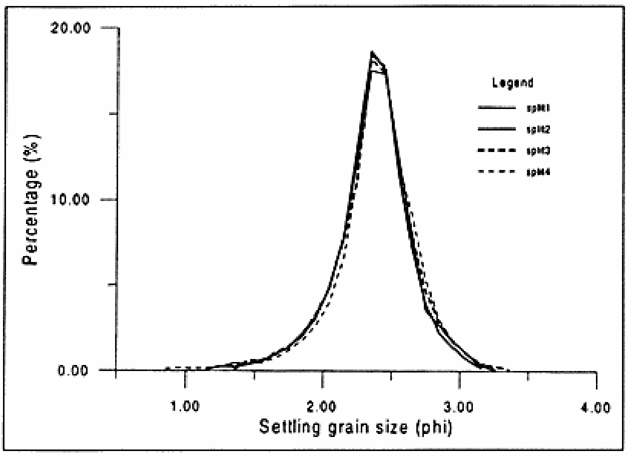

Figure 2: The grain size distributions of 4 (1g) sub samples of dune sand from Skallingen, illustrating the reproducibility of the single sample splits. The statistical parameters of all four samples are: Mz = 2.385 phi , Sd = 0.247 phi , Sk = - 0.066 and Kg = 0.958. The mean of the two subsample pairs which deviate the most (A and B) give: A) Mz = 2.392 phi, Sd = 0.251 phi, Sk = - 0.070 and Kg = 0.961; B) Mz = 2.378 phi, Sd = 0.244 phi, Sk = - 0.062 and Kg = 0.955.

Sieve diameter versus settling diameter

The samples used in this analysis represent 4 major sedimentary environments in the southwestern part of Denmark:

1) The rivers leading to the Danish Wadden Sea, represented by sand from the river Ribe Å (Vinsløv, 1998) (6 samples).

2) The intertidal area of the Danish Wadden Sea, represented by sand from the tidal area Hobo Dyb (Bartholdy, 1983 , 1997) (2 samples analysed in sieve fractions).

3) The North Sea beach of the Danish Wadden Sea islands, represented by sand from the central part of the barrier spit Skallingen (this study) (5 samples).

4) Aeolian dunes on the Danish Wadden Sea islands, represented by sand from the central part of the barrier Skallingen spit (this study) (10 samples).

As the characteristics of the investigated sand fractions from all 4 sedimentary environments turned out to be remarkably uniform and as the primary objective of this paper is to describe and analyse similarities and differences between the two methods of grain-size analysis, a closer description of the four sedimentary environments is not relevant here. Interested readers are referred to Bartholdy et al., 1991(1); Bartholdy & Pejrup, 1994 (2,3); Bartholdy & Kisling-Møller, 1996(1); Aagaard et al. 1995(3,4); Bartholdy, 1997(2,3,4).

Analysis of sieved sand fractions

Based on the mean results of the sieve fractions from all 4 environments (67 sieved sand fractions), Figure 3 describes the settling diameter as a function of the mean diameter of the sieved sub-fractions. The uniformity between these four environments is remarkable and the results suggest no tendency for any of the individual environments to deviate significantly from the following mean linear relationship:

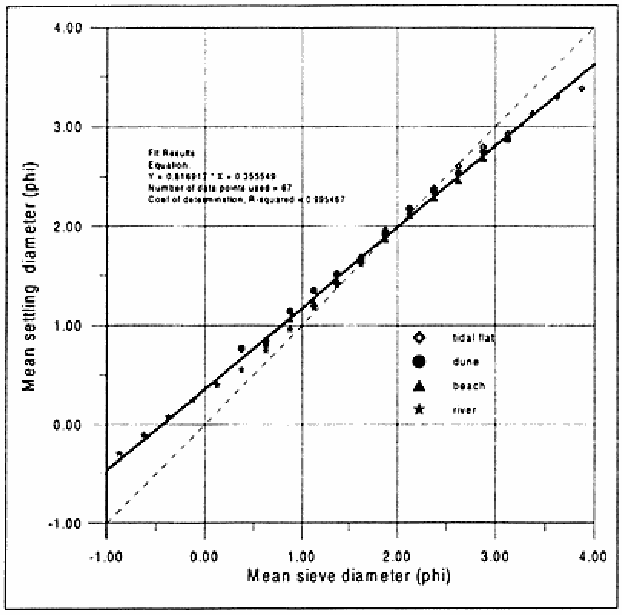

Figure 3: Settling diameter (phi) as a function of sieve diameter (phi) based on sieved grain-size fractions (1/4-phi) analysed in the Macrogranometer. The regression is based on 12 total samples grouped into 4 series (one for each environment) with a total of 67 points. The regression coefficient is 0.995. The grain density is 2650 kg/m³ and the settling diameter is based on that of a smooth sphere.

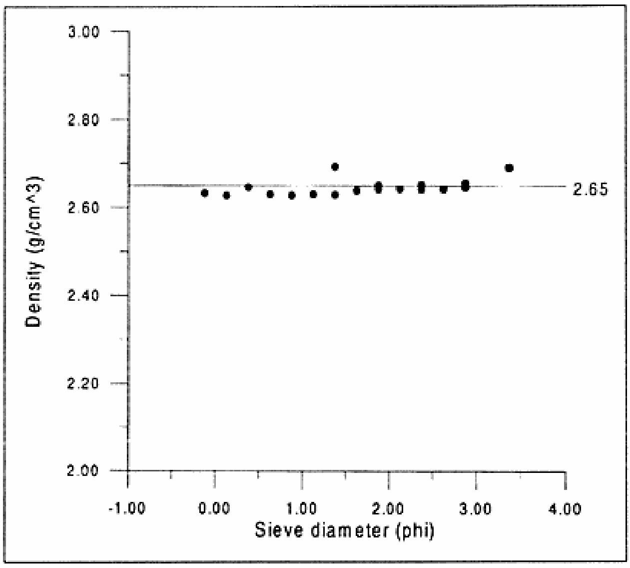

Figure 4: Grain density as function of grain size. The results are based on pycnometer analysis of sieved (1/4-phi) sand fractions.

$$d_{set} = 0.8169 d_{siv} + 0.3555 \qquad (7)$$

$$d_{siv} = 1.2442 d_{set} - 0.5473 \qquad (8)$$

d_{siv} and d_{set} being the sieve and the settling diameters (phi units). These results are very similar to those obtained by Flemming & Ziegler (1995) on the basis of 5 samples from the East Frisian Wadden Sea treated in the same way:

$$d_{set} = 0.7983 d_{siv} + 0.4605 \qquad (9)$$

The relationship indicates that for sand finer than approximately 2 phi (0.250 mm), the settling diameter is larger than the sieve diameter and for sand coarser than 2 phi the settling diameter is smaller than the sieve diameter. This trend could be caused by a grain-size dependent change in either density or shape.

The densities of the sieved sub-fractions were checked by means of a pycnometer test (Borggaard & Møberg, 1974). The results shown in Figure 4 reveal that the density of the sand in all subsamples is in accordance with the density of quartz (2650 kg m^{-3}). The small variations in density shown in Figure 4 can be regarded as uncertainties induced by the measuring procedure. It can, therefore, be safely assumed that density variations are not responsible for the systematic departures between sieve and settling diameters.

The shape change between the sand fractions was examined by calculating the volume diameter of the single fractions. This was conducted based on the weight of a subsample of particles counted under the microscope. With an assumed density of the grains of 2650 kg m^{-3}, the mean volume diameter of the counted grains was calculated from their average weight. The results (Figure 5), demonstrate an almost linear relationship between the sieve diameter and the volume diameter, which satisfies the condition of a gradually increasing difference between the two. The following equation (phi-units), which describes the relationship between the volume diameter and corresponding sieve diameter, has a coefficient of determination (R-squared) of 0.996 :

$$d_{vol} = 0.9394 d_{siv} - 0.1032 \qquad (10)$$

Since the sieve mesh openings can be considered to be uniform, this increasing difference between volume diameter and sieve diameter, as grain size gets finer, can only be rationally explained by an increasing number of elongated particles in the smaller grain-size classes. Elongation is the only possible way to increase the volume

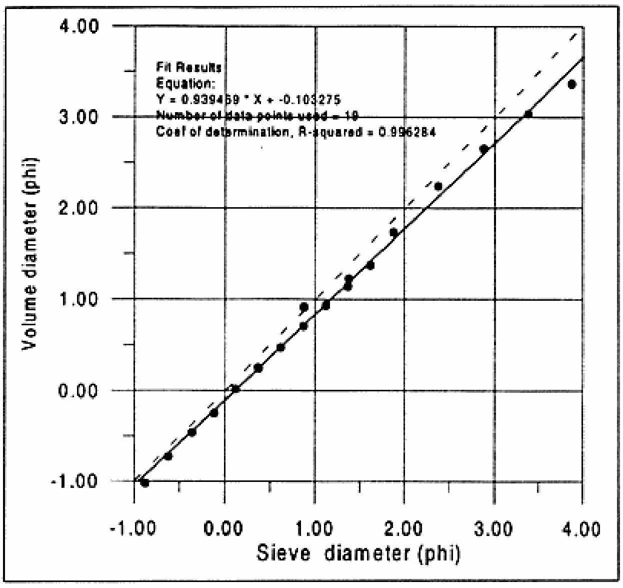

Figure 5: *Volume diameter as a function of sieve diameter in 1/4-phi sieved subsamples. The linear regression coefficient is 0.996.*

of a particle passing through a fixed sieve opening. The reason for this tendency for finer quartz grains to be more elongated than coarser grains can be a result of natural wear and/or of mineralogical conditions in the source rocks of the sand. Unfortunately this aspect can not be further elucidated on the basis of the present data.

Using Eq. 10 and Eq. 8 the relationship between volume and settling diameter can be expressed as:

$$d_{vol} = 1.1688 d_{sett} - 0.4109 \qquad (11)$$

This relationship shows that the volume diameter is more or less equal to the settling diameter at the fine end, but that it increases relatively to the settling diameter as the sediment gets coarser. Thus, the settling diameter is almost 0.3 phi finer than the volume diameter at the upper limit of coarse sand. This is in accordance with the fact that the hydraulic resistance of irregular grains increases as the settling velocity increases. Based on the results, it is possible to explain the variation between the sieve and settling diameters by the combined effect of: **1)** increasing hydraulic resistance with grain size for naturally worn irregular particles *and* **2)** a raised volume diameter relative to the sieve diameter as the particle gets finer. The latter aspect dominates in fine and very fine sands, whereas the former dominates in the coarser grain size. The two appear to balance out around 2phi(0.25mm) where the settling velocity of the naturally worn grains equals that of a smooth sphere.

Statistical parameters

The variations in the statistical parameters when going from sieve to settling analysis are illustrated in Figure 6. The tidal flat sediments are excluded because they were only available as individual sieved fractions (Bartholdy, 1983). For the mean grain size (Fig. 6a) and the sorting (Fig. 6b), the changes are straightforward. The mean settling diameters are slightly coarser for the fine sand and somewhat finer for the coarser fluvial sand. This is in accordance with the results of the single fraction data shown in Figure 3. The sorting of the settling data is better than that of the sieve data for all grain sizes. This is also in accordance with the results shown in Figure 3 where the settling diameters of all finer and coarser sands tend to converge towards 2phi(0.25mm) from both size directions. It then follows that for any given sieve size range, the corresponding settling size range should be smaller. For the skewness (Fig. 6c), the changes are less straightforward. All the samples analysed in this study were found to be negatively skewed and there seems to be a pattern where the fluvial samples have a tendency towards a less negatively skewed settling distribution, whereas the opposite is the case for the finer beach and dune samples. This tendency could be a result of a suppression of coarse tails in the coarse sediments and a corresponding suppression of fine tails in the fine sand. As a particular fraction finer than 2 phi (0.250 mm)is shifted towards the coarse side when going from sieve diameters to settling diameters (Figure 3), this has a damping influence of a fine tail in the grain size range between 2 phi and 4 phi (0.250 mm - 0.063 mm). Conversely, a corresponding fraction coarser than 2 phi (0.250 mm) is shifted towards the fine side, and will hence dampen the effect of a coarse tail in grain size range between -1 phi (2mm) and 2 phi (0.25mm). Such dampening causes the skewness to change in accordance with the observed pattern. As for the Kurtosis (Figure 6d), the tendency is towards a higher value when going from sieve to settling for the well sorted dune samples while there are only small changes in the slightly less well sorted (sieve) beach and less well sorted fluvial samples (see Figure 6b). This is primarily because the higher resolution of the settling analysis (0.02 phi) more accurately records the modal peak of the distribution.

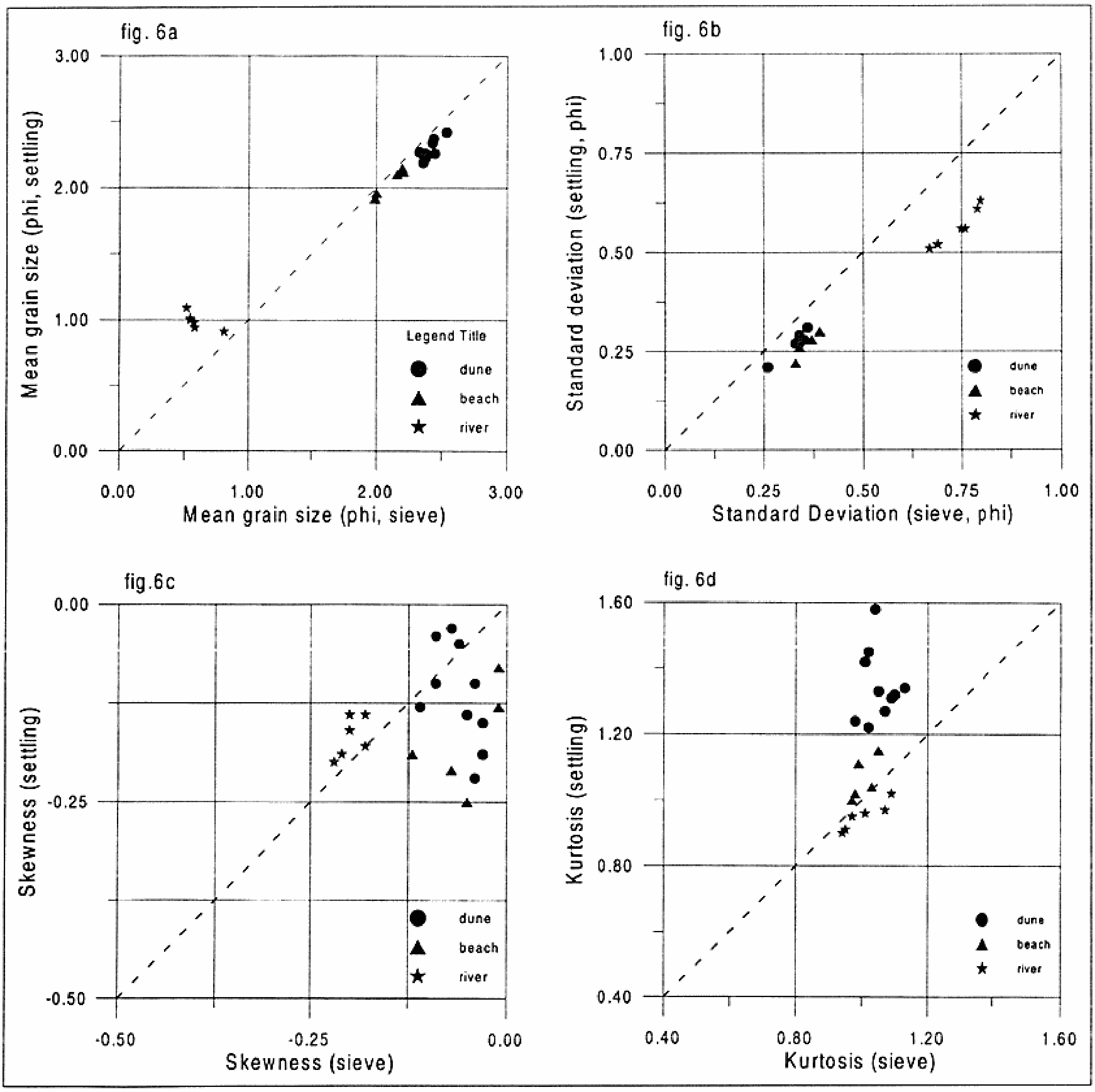

Figure 6: a) Mean grain sizes based on sieve diameter versus mean grain sizes based on settling diameter; b) Standarddeviations of grain size distributions based on sieve diameter versus standard deviations based on settling diameter, c) skewness of grain size distributions based on sieve diameter versus skewness based on settling diameter; d) kurtosis of grain size distributions based on sieve diameter versus kurtosis based on settling diameter.

This peak will be much more pronounced for well sorted sediments analysed with a resolution of 0.02 phi than is the case when it can hide in the much cruder 1/4 phi resolution of the sieved analysis.

Comparing the result of both methods of grain size analysis (Figure 6) the results of the 21 samples from the dune, beach and fluvial environments in general confirm the expected changes in the statistical parameters when going from sieve to settling analysis: 1) sieve-based grain sizes finer than 2 phi correspond to coarser settling diameters, while coarser sieve-based sand fractions correspond to a finer settling diameters; 2) the sorting gets better; 3) generally, fine well-sorted sediments with a negative skewness become more negatively skewed, whereas coarser and less well-sorted sediments become more positively skewed, *and* 4) the kurtosis of the distributions increases for well sorted sediments. The pattern is very clear for the mean grain size and the sorting, but less obvious, for the skewness and the kurtosis.

Summary and conclusions

The optimal sample size for analysing sand in a settling tube has been examined on the basis of sieved subfractions of different size classes. Investigating the effect of different concentrations of grains introduced in a settling tube, it was found that an areal concentration α of 0,04 ($\alpha = n \cdot d_{set}^2/d_{tube}^2$) represents the maximum concentration beyond which artificially increased settling velocities begin to bias the results. This concentration can be recalculated to a sample size as a function of grain size and tube diameter by means of the following equation:

$$\text{Sample size} = k \cdot d_s \cdot d_{tube}^2 \text{ (SI units)}$$

Where k has a constant value of 55.4 (kg m^{-3}). With a careful sample splitting procedure, this sample size was found to be optimal.

The difference in the textural response between the sieve and the settling methods was examined in four different sedimentary environments in southwest Denmark. The settling diameter was defined as that of a smooth sphere having the same settling velocity as the sediment grain. Samples from the rivers, the Wadden Sea, the North Sea coast and aeolian dunes gave the following relationship between sieve diameter and settling diameter with a coefficient of determination (r^2) of 0.995:

$$d_{set} = 0.8169 d_{siv} + 0.3555 \text{ (phi unit)}$$

This relationship was similar to that observed in the East Frisian Wadden Sea (Flemming & Ziegler, 1995). It shows that the settling diameters are larger than the sieve diameters for sand finer than approximately 2 phi (0.250 mm), and smaller for coarser grain sizes.

The density of sieved sand fractions was examined using a pycnometer test and it was found that the density was uniform and did not differ from that of quartz (2650 kg m^{-3}). This indicates that density differences were not responsible for the systemic deviation between sieve diameter and settling diameter. The following linear relationship ($r^2 = 0.996$) was found between sieve diameters and volume diameters:

$$d_{vol} = 0.9394 d_{siv} - 0.1032 \text{ (phi unit)}$$

Combining the relation between sieve diameter and settling diameter with this relation gives:

$$d_{vol} = 1.1688 d_{set} - 0.4109 \text{ (phi unit)}$$

Based on these results the variation between the sieve and settling diameters is interpreted to be caused by a larger volume diameter in the fine grain-size classes combined with a greater influence of the hydraulic resistance of irregular grains as the settling velocity becomes larger.

When changing from sieve to settling diameters, the statistical parameters (Folk & Ward, 1957) of the grain-size distributions were found to react in the following manner: 1) sieve-based grain sizes finer than 2 phi correspond to coarser settling diameters, while coarser sieve-based sand fractions correspond to finer settling diameters; 2) the sorting gets better; 3) generally, fine well-sorted sediments with a negative skewness become more negatively skewed, whereas coarser and less well-sorted sediments become more positively skewed, *and* 4) the kurtosis of the distributions increases for well sorted sediments. The pattern is very clear for the mean grain size and the sorting, but less obvious, for the skewness and the kurtosis.

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